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Monterey, California

A MATHEMATICAL FORMULATION FOR SELECTING

HOLDING-TANK-PROCESSOR REQUIREMENTS

FOR SHIPBOARD SEWAGE TREATMENT

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ABSTRACT:

This paper describes a formulation of the problem that systems designers face in selecting a combination of holding tank and processor for shipboard sewage treatment systems. Two decision models are discussed within this framework. In one case the generation of sewage, aboard ships, is assumed to consist of deterministic arrival streams. In a second model, sewage generation is assumed to behave in accordance with a Poisson process. Allowances for maintenance and reliability are discussed.

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Prepared by:

1. INTRODUCTION

Our increasing concern for a clean environment, and recent legislation by the United States Congress in support of this concern have prompted the U.S. Navy to expedite their efforts to eliminate the discharge of sewage in inland waters. To date, it appears that there are two alternative directions available to the Navy: (1) to make shore connections with municipal sewage treatment systems, and (2) to provide on-board sewage treatment facilities. Although the first alternative is appealing because of its simplicity and apparently lower initial investment cost, it has several disadvantages. Since municipal cooperation is required, the Navy stands to lose mobile flexibility unless such cooperation can be sustained indefinitely with each coastal municipality, both domestic and foreign. The actual cost for this is not known. Furthermore, there are other costs that would have to be incurred over and above the "connection costs." Every naval vessel would be required to have an on-board pumping system, plus a holding tank system for collecting sewage generated while in-transit or at anchorage.

The second alternative direction indeed offers sustained mobile flexibility for the Navy, but the initial investment can be very high. Several shipboard treatment facilities have been proposed [1]. These consist of a chemical or bacteriological treatment process coupled with a holding tank system. Unfortunately,

to date, none of these systems have proven to be effective. Although cost is an important factor, other reasons that contribute to this defeat is the lack of capability to meet anticipated Environmental Pollution Agency (EPA) standards and a host of interfacing problems in implementing proposed designs aboard ships.

The approach to the development of these shipboard treatment systems has been one of building a set of hardware in one phase, followed by an implementation phase where a ship and crew must accomodate the new facility. Another approach is to prescribe the needs of the ship and design the hardware accordingly. Since we now have some knowledge of our hardware development capabilities, perhaps this latter approach is in order.

This paper describes a mathematical formulation for examining trade-offs between holding tank capacity and processing rates of any proposed facility subject to the restriction that all sewage generated must be processed (i.e., no overflow of unprocessed effluent). Following a general formulation of the problem in section 2, we shall consider the case where the generation of sewage is assumed to be deterministic in section 3. In section 4, we consider the more general case where arrival streams are random but we assume that the distribution is Poisson. Section 5 discusses the effect of interrupted operation of the processor, followed by final comments in section 6.

2. PROBLEM FORUMLATION

The problem to be studied involves an arrival stream of sewage, aboard a naval vessel, to a collection point where it is stored in a tank for processing and removal from the parent facility. We shall consider this arrival stream as countable numbers of a fixed volume of sewage that are generated at discrete points in time. This problem is essentially the same as the "dam", or storage, problem which has received considerable attention in the literature over the past several years (see Moran [3] and Prabhu [4]). In particular, random inputs accumulate in a finite capacity storage facility (provided the capacity is not exceeded) with outputs that depend both on the volume accumulated and the release policy employed. The analytical detail provided by storage theory, however, far exceeds that of our current understanding of the nature of sewage generation aboard ships. For this reason, we limit our present discussion to a formal treatment of the decision problem of selecting combinations of holding tank and processing capabilities.

From the point of view of a systems designer, his role is that of a decision maker whose objective is to make an appropriate selection of processor and holding tank system. Among his alternatives are various combinations of processing units and tank sizes each of which has associated costs. His constraints are determined by cost, space utilization, risk of overflow of effluent sewage, and reliability.

Basically, this is a decision problem in which the decision maker is uncertain as to the "future states of nature." In this case nature corresponds to the characteristics of sewage generation by shipboard crews. For each alternative, i.e., combination of processor and holding tank, and possible state of nature there is a cost value that depends upon a set of constraints. Our problem is to find a decision rule for solving choice among the alternatives.

In general, one can treat the problem as a decision under risk by assuming knowledge of the probability structure of the future generation of sewage. Before we take this approach, however, we shall consider a more simplified approach by assuming complete knowledge of the generation of sewage aboard ships. Our motivation for this latter approach is based on the relatively systematic shipboard routine.

3. DETERMINISTIC ARRIVAL STREAMS

3.1 Constant Arrival Rates

Consider an arrival stream of sewage to a shipboard holding tank of capacity V. The stream alternates deterministically between two rates, r_1 and r_2, over a period of time of length τ. Thus, the arrival rate is given by

$$\mu(t) = \begin{cases} r_1 , & \text{if} \quad 0 \le t \le \gamma\tau \\ r_2 , & \text{if} \quad \gamma\tau \le t \le \tau \end{cases} \tag{1}$$

where $0 \leq \gamma \leq 1$ and $r_1 > r_2$. This is shown in Figure 1.

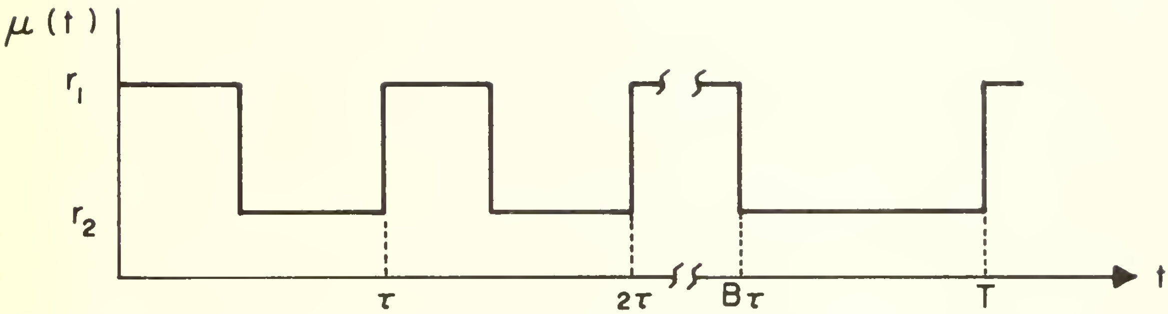

Fig. 1. A typical deterministic arrival stream with $\gamma = 1/3$. Note that $\mu(t) = r_2$ for $B\tau \leq t \leq T = W\tau$.

A cycle of length T comprises an integer number W of these periods of length τ. The first $B < W$, also an integer, of these periods are repetitions and have arrival rates given by equation (1). For the remaining time duration $(W-B)\tau$, the rate is r_2.

From the holding tank, sewage is processed at a constant rate α. Thus, the net accumulation in the holding tank during τ for any one of the first B periods is given by

$$M(\tau) = \left\{\int_{o}^{\gamma\tau} (r_1-\alpha)\ dt + \int_{\gamma\tau}^{\tau} (r_2-\alpha)\ dt\right\}^+$$

(2)

$$= \tau[\gamma r_1 + (1-\gamma)r_2 - \alpha]^+ .$$

There are two cases to consider. First, for $\alpha > \gamma r_1 + (1-\gamma)r_2$, $M(\tau) = 0$ and there will be idle processor time during period τ in the amount

$$t_i = \frac{\tau[\gamma r_1 + (1-\gamma)r_2 - \alpha]}{r_2 - \alpha} .$$

The maximum accumulation for this case will occur at $\tau = \gamma\tau$. Thus,

$$M_{max}(\gamma\tau) = (r_1-\alpha)\gamma\tau \quad ,$$

and this will be the minimum tank volume that will insure against overflow.

The second case to consider is where $M(\tau) > 0$. Here the maximum accumulation in the tank will occur at the earliest time t_m such that $\mu(t) < \alpha$ for all $t : t_m \leq t \leq T$, which will be $\gamma\tau$ time units into period B. Since the tank capacity V must exceed $M_{max}(t)$ in order to prevent overflows,

$$M_{max}(t) = (B-1)M(\tau) + \gamma\tau(r_1-\alpha) \leq V$$

from which it follows that

$$(3) \qquad V + \tau(B-1+\gamma)\alpha \geq \tau[B\gamma r_1 + (B-1)(1-\gamma)r_2] \ .$$

We shall impose the restriction that the system processes all arrivals in each cycle, i.e., $M(T) = 0$, therefore, the processing capacity must exceed the volume generated. Thus,

$$W\tau\alpha \geq \tau[B\gamma r_1 + (W-\gamma B)r_2]$$

or

$$(4) \qquad \alpha \geq \frac{B\gamma r_1 + (W-\gamma B)r_2}{W}$$

This is equivalent to requiring that the amount of sewage processed in $[t_m, T]$ be greater than $M_{max}(t)$ plus the amount of sewage generated in $[t_m, T]$. It is noted that if $\alpha > r_1$, then the only holding tank requirement would be to accomodate the accumulation during maintenance periods. Hence, the range of interest for α is

$$(5) \qquad \frac{B\gamma r_1 + (W-\gamma Br_2)}{W} \leq \alpha \leq r_1 \ .$$

Let us now consider the decision problem of selecting an appropriate system for a particular ship. Any processing system has associated costs which we shall assume can be related to processing

rate, holding tank capacity, and spatial requirements. From the above we can determine the minimum holding tank size required to satisfy the system requirements. For each of $i = 1, \ldots, n$ candidate systems let $C_{1i}(\alpha)$ be the cost to process at rate α, and $C_{2i}(V)$ the cost associated with a capacity V. For simplicity, we are including the spacial requirements for the processor with the holding tank volume. Our problem then is the following mathematical programming problem:

$$\min \quad C_i = C_{1i}(\alpha) + C_{2i}(V)$$

$$\text{(P)} \qquad \text{s.t.:} \quad V + \tau(B-1+\gamma)\alpha \geq \tau[B\gamma r_1 + (B-1)(1-\gamma)r_2]$$

$$\alpha \geq \frac{B\gamma r_1 + (W-\gamma B)r_2}{W}$$

$$\alpha \geq 0 \quad , \quad V \geq 0 \quad .$$

The solution to (P) determines a set of optimal values $(\tilde{\alpha},\tilde{V})$; for each candidate system $i = 1,\ldots,n$. The minimum cost then is $C^* = \min\limits_i C_i$, and our decision rule is to select $i^* = \{i\colon \; C_i = C^*\}$.

<u>Example - 1</u>

To illustrate the approach described in this section, consider the situation where sewage generation is relatively constant at 216 gal./hr. for the first 40 percent of a workday. At the end of

this duration, the rate instantaneously drops to 108 gal./day and reamins at that level for the remaining 60 percent. Our cycle is 1 week in duration which is comprised of 5 workdays by a 2 day weekend. Thus we have,

$$\tau = 24 \text{ hours}$$

$$W = 7 \text{ days}$$

$$B = 5 \text{ days}$$

$$\gamma = 0.4$$

$$r_1 = 216 \text{ gal./hr}$$

$$r_2 = 108 \text{ gal./hr.}$$

The net accumulation during a workday, from equation (2), is

$$M(\tau) = 24[151.2 - \alpha]^+ ,$$

and from equation (5) the range of interest for α is

$$138\tfrac{6}{7} \le \alpha \le 216 \text{ gal./hr.}$$

Therefore;

$$138\tfrac{6}{7} \le \alpha \le 151.2 \text{ gal./hr.}$$

determines a critical area in which there is a gradual accumulation of stored sewage during the week, which is to be processed over the

weekend. For this range, on applying the inequality of equation (3), we have

$$V + 105\alpha \geq 16{,}588.8 \text{ gal.}$$

Problem (P) then is

$$\min \; C_i$$

$$\text{s.t.:} \quad V + 105\alpha \geq 16{,}588.8$$

$$\alpha \geq 138.86$$

$$V, \alpha \geq 0 \; .$$

In this section we have assumed that the generation of sewage was both deterministic and constant at fixed known durations of time. The systems designer will indeed have to make allowances for these assumptions. In general; he will solve problem (P) for many representative values of B, W, τ, r_1, r_2, and γ, and determine a range of values for a subset of the candidate systems. He then, of course, must apply judgment. In some cases, however, he cannot justify assuming that the rates are constant even though he might be able to assume that they are deterministic.

3.2 Variable Arrival Rate-Fourier Series Approach

Let us now consider deterministic arrival streams that are variable, but identical for B periods each of length τ.

Any cyclic arrival stream may be represented by a sum of cosine and sine terms of increasing harmonics. For illustration, a typical arrival flow in terms of an incremental volume may be represented by the Fourier series:

$$v(t) = A_o - A_1 \cos 2\pi \frac{t}{\tau} - A_2 \cos 4\pi \frac{t}{\tau} . \tag{6}$$

The total volume of sewage generated in a period is

$$A_o = \int_o^{\tau} v(t)\, dt \tag{7}$$

and the net accumulation of sewage over time t

$$M(t) = \int_o^{t} [v(u) - \alpha]\, du , \tag{8}$$

for suitable values[1] of A_o, A_1 and A_2. Letting t_1 and t_2 be the first and last times that $v(t) = \alpha$ over length τ, it is convenient to translate the origin to t_1. Thus,

$$M_{max}(t) = \max_{t_m} \int_{t_1}^{t_m} [v(t) - \alpha]dt , \tag{9}$$

and for the simple case shown in Figure 2,

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[1] provided $\int_o^{w} [v(u) - \alpha]du \geq 0$ for all $w \leq t$. We shall spare the details here.

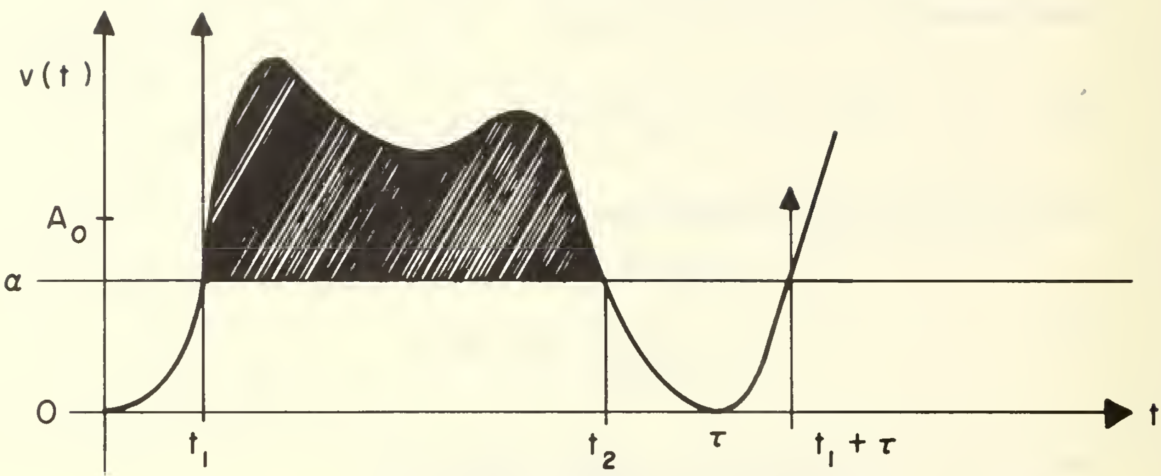

Fig. 2. A variable arrival stream showing periods of of over – production ($v(t) \geq \alpha$; hatched) and under production.

$$M_{max}(t) = M(t_2) = [A_o - \alpha]\,(t_2 - t_1)$$

$$- \frac{A_1\tau}{2\pi} \sin \frac{2\tau t_2}{\tau} + \frac{A_1\tau}{2\pi} \sin \frac{2\pi t_1}{\tau}$$

$$- \frac{A_2\tau}{4\pi} \sin \frac{4\pi t_2}{\tau} + \frac{A_2\tau}{4\pi} \sin \frac{4\pi t_1}{\tau} .$$

This is the hatched area in Figure 2.

We have ignored the remaining $(W-B)\tau$ time units of the cycle of length T. In practice, of course, one would apply the above technique to this interval of time and determine an approximation for the overall arrival behavior. Again, the system designer will have to apply judgment. We shall next consider the situation where arrivals of sewage to the holding tank are random.

4. RANDOM ARRIVAL STREAMS

4.1 Poisson Arrivals

Assume that the counting process, $N(t)$, for quantities of sewage is Poisson with rate λ. Each i^{th} arrival consists of a volume of amount denoted by random variable Y_i. Thus, the amount of sewage generated prior to some time t is given by

$$X(t) = \sum_{i=1}^{N(t)} Y_i \,, \tag{10}$$

and $\{X(t)\ ;\ t \geq 0\}$ is a compound Poisson process. For the special case where each arrival is a fixed volume Q, i.e., $Y_i = Q$ for all i,

$$X(t) = Q\, N(t) \tag{11}$$

and

$$E[X(t)] = Q\, E[N(t)] = Q\, \lambda t \,. \tag{12}$$

We shall now consider the stochastic analog to the arrival pattern described in section 3.1. For time period of length τ, the rate λ alternates between two constant values, at a fixed point $\gamma\tau$, given by

$$(13) \qquad \lambda(t) = \begin{cases} r_1 & , \quad 0 \le t \le \gamma\tau \\ r_2 & , \quad \gamma\tau \le t \le \tau \ . \end{cases}$$

Thus, the arrival process is described by the two processes $\{N_1(t) \ ; \ t \ge 0\}$ and $\{N_2(t) \ ; \ t \ge 0\}$ with parameters r_1 and r_2 respectively. Assuming $X(0) > 0$, the amount of accumulation in a tank at time t is

$$(14) \qquad M(t) = X(t) - t\alpha = Q\ N(t) - t\alpha$$

provided $X(u) - u\alpha > 0$ for all $u\varepsilon(0,t)$. Here we assume that $X(0)$ and r_1 are both sufficiently large, so that the probability of remaining at a boundary, i.e. V or 0, is small. This is reasonable aboard most ships particularly since if the input rate is very small, then it is impractical to process. Thus, for a period

$$(15) \qquad \begin{aligned} M(\tau) &= M(\gamma\tau) + M((1-\gamma)\tau) \\ &= Q[N_1(\gamma\tau) + N_2((1-\gamma)\tau)] - \tau\alpha \end{aligned}$$

and for $M(\tau) > 0$,

(16a) $$E[M(\tau)] = Q[r_1\gamma\tau + r_2(1-\gamma)\tau] - \alpha\tau$$

and

(16b) $$\mathrm{Var}[M(\tau)] = Q^2[r_1\gamma\tau + r_2(1-\gamma)\tau] .$$

As with the case of deterministic arrival streams, described in section 3, we restrict the tank capacity V by the maximum accumulation over a cycle of length T. Hence,

$$P\{M_{max}(t) \le V\} \ge \xi_1 \quad , \quad (0 \le t \le T \, , \, 0 \le \xi_1 \le 1) \, ,$$

or

$$P\{(B-1)(Q[N_1(\gamma\tau) + N_2((1-\gamma)\tau)] - \tau\alpha)$$

$$+ Q\, N_1(\gamma\tau) - \gamma\tau\alpha \le V\} \ge \xi_1 \quad ,$$

from which it follows that

(17) $$P\left\{N_{a1}(\tau) \le \frac{V + (B-1+\gamma)\tau\alpha}{Q}\right\} \ge \xi_1$$

where $N_{a1}(\tau)$ is Poisson distributed with parameter

$$\lambda_{a1} = [B\gamma r_1 + (B-1)(1-\gamma)r_2]\tau .$$

Similarly, the requirement that all sewage generated is processed during each cycle becomes

$$P\{B\ M(\tau) + (W-B)Q\ N_2(\tau) - (W-B)\tau\alpha \le 0\} \ge \xi_2 \ , \ (0 \le \xi_2 \le 1) \ .$$

This leads to

$$P\{N_{a2}(\tau) \le \frac{W\tau\alpha}{Q}\} \ge \xi_2 \tag{18}$$

where $N_{a2}(\tau)$ is Poisson distributed with parameter

$$\lambda_{a2} = B\gamma\tau r_1 + (W-\gamma B)\tau r_2 \ .$$

The decision problem for the case of Poisson arrival streams may now be formulated, similar to problem (P) in section 3. Letting,

$$Z_1 = \frac{V + (B-1+\gamma)\tau\alpha}{Q}$$

$$Z_2 = \frac{W\tau\alpha}{Q} \quad ,$$

we wish to

$$\text{(P}'\text{)} \qquad \begin{aligned} &\min \quad C_i = C_{1i}(\alpha) + C_{2i}(V) \\ &\text{s.t.} \quad \sum_{i=1}^{\langle Z_1 \rangle} \frac{\lambda_{a1}^{i} e^{-\lambda_{a1}}}{i!} \ge \xi_1 \\ &\qquad\ \ \sum_{i=1}^{\langle Z_2 \rangle} \frac{\lambda_{a2}^{i} e^{-\lambda_{a2}}}{i!} \ge \xi_2 \\ &\qquad\ \ \alpha \ge 0 \quad , \quad V \ge 0 \end{aligned}$$

where the symbol "< >" denotes greatest integer.

4.2 Normal Approximation

It is well known that for large values of λ, Poisson distributed $N(t)$ can be approximated by a Normal density function. Therefore; since

$$M(t_m) = Q\, N_1(\gamma\tau) - \gamma\tau\alpha \ ,$$

(19) $$M(t_m) \overset{a}{\sim} N[E(M(t_m)),\ \ Var(M(t_m))] \ .$$

Thus, for $M(\tau) \leq 0$, the tank capacity V must be such that

$$V \geq E(M(t_m)) + \Phi^{-1}(1-\xi_1)[Var(M(t_m))]^{1/2}$$

or

(20) $$V \geq Q\gamma\tau r_1 - \gamma\tau\alpha + \Phi^{-1}(1-\xi_1)[\gamma\tau r_1]^{1/2}Q$$

in order to have the probability of overflow less than $1 - \xi_1$. In a similar manner, for $M(\tau) > 0$, it can be shown that

(21) $$V + (B-1+\gamma)\tau\alpha \geq B\gamma\tau Q r_1 + (B-1)(1-\gamma)\tau Q r_2 + \Phi^{-1}(1-\xi_1)[\gamma\tau r_1]^{1/2}Q \ .$$

For the additional requirement that all sewage generated in a cycle be processed, in the same cycle, with probability ξ_2,

$$E(M(T)) + \Phi^{-1}(1-\xi_2)[\mathrm{Var}(M(T))]^{1/2} \leq 0 \tag{22}$$

where

$$E(M(T)) = Q[B\gamma\tau r_1 + (W-\gamma B)\tau r_2] - W\tau\alpha \tag{23a}$$

$$\mathrm{Var}(M(T)) = Q^2[B\gamma\tau r_1 + (W-\gamma B)\tau r_2] . \tag{23b}$$

Hence, it follows that

$$\alpha \geq \frac{Q}{W\tau}\{[B\gamma\tau r_1 + (W-\gamma B)\tau r_2] + \Phi^{-1}(1-\xi_2)[B\gamma\tau r_1 + (W-\gamma B)\tau r_2]^{1/2} . \tag{24}$$

The decision problem (P'), using the normal approximation for Poisson arrivals of sewage, is to $\min_i C_i$ subject to the constraints given by equations (20), (21) and (24).

Example - 2

For illustration of the above; consider again the data of Example - 1, but with r_1 and r_2 now in units of arrivals/hour. Letting $Q = 4.5$ gallons per arrival,

$Qr_1 = 216$ gal./hr. $\qquad Qr_2 = 108$ gal./hr.

$\lambda a_1 = 3686.4 \qquad Z_{a1} = \dfrac{V + 105.6\alpha}{4.5}$

$\lambda_{a2} = 5184 \qquad Z_{a2} = 37.33\alpha$

Since λ_{a1} and λ_{a2} are large, we shall use the Normal approximation. For $\xi_1 = \xi_2 = 0.975$, the constraint of equation (20) is

$$V + 105.6\alpha \geq 16{,}778.1 \text{ gal.}$$

and from equation (24)

$$\alpha \geq 142.6 \text{ gal./hr.}$$

5. INTERRUPTED OPERATION OF PROCESSOR

The fact that no system is infallible makes it necessary for systems designers to consider some form of allowance for "down time", or interrupted service time of the processor. This down time comprises planned periods for preventive maintenance as well as unplanned periods that arise due to electrical and mechanical malfunctions. In either case, the holding tank must be of sufficient capacity to accomodate the additional sewage that accumulates during these interruptions.

One way in which the designer can make allowances for down time is to apply a safety factor to the tank capacity determined by solving program P or P'. Alternatively, he may incorporate this allowance in the analysis by modifying the constraints in the decision problem. For example, the worst situation arises when a down time period of length D commences at the time, t_m, of maximum accumulation in the tank. For the case of Poisson arrival

streams, discussed in section 4, one can allow for this by examining

$$M_{max}(t_m') = M_{max}(t_m) + Q\ N_2(D)\ . \tag{25}$$

Since D depends upon the reliability and maintainability requirements for a particular system, it will vary in length among different processing systems.

6. FINAL COMMENTS

The foregoing sections provide a descriptive framework for the decision problem of selecting combined holding-tank-processor systems for shipboard sewage treatment. Like any decision problem; the decision maker, systems designer in this case, must tradeoff between simplicity and reality through assumptions, and supplement his final analysis with judgment. In general; the more uncertain he is of the distribution of sewage generated, the more judgment he will be required to make.

There are, of course, situations where the generation of sewage cannot be treated deterministic, as in section 3, nor can it be described by a Poisson process (section 4). The general approach presented in this study, however, is not limited to these two models. Given more complete knowledge of a particular sewage generation process, one can arrive at a better choice of facilities. Miner [2] has recently developed an empirical distribution of the

generation of shipboard sewage based on known data available to date and subjective ratings by shipboard personnel. He also examined the sensitivity of holding tank capacity to various shipboard operating policies.

Only the case of a single holding tank and processor have been considered in both this study and the study by Miner. For large ships it may be necessary to combine one or more holding tanks with one or more processors. It is suggested that future studies address this problem.

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13. ABSTRACT

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